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SOLAR TURBINES INTERNATIONAL SAN DIEGO CA
COMBINED CYCLE STEAM GENERATOR GAS SIDE FOULING EVALUATION. (U)
SEP 80 P B ROBERTS, A J KUBASCO

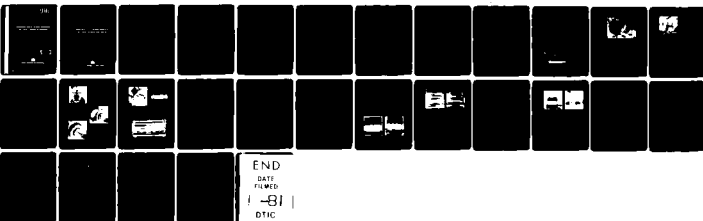
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**Combined Cycle Steam Generator
Gas Side Fouling Evaluation.**

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PHASE 2 FINAL REPORT. Phase 2,

11 September 1980

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Prepared Under Contract Number N00024-77-C-4366 for
Naval Sea Systems Command
Department of the Navy

P.E. Roberts
A.J. Kubacki

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Combined Cycle Steam Generator Gas Side Fouling Evaluation

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ABSTRACT

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Liquid-fueled gas turbines can produce serious steam generator fouling in gas turbine combined cycle applications and other waste heat recovery systems as a result of combustion system generated soot particles. In addition, standard soot blowing practices are not always compatible with the advanced, compact matrix designs sometimes required for minimum package size applications.

In Phase I, an experimental program was conducted on both test rigs and engine hardware designed to evaluate the effects on gas side soot fouling rates of various operational parameters such as soot loading, temperature, and velocity. Results showed that the self-cleaning concept, whereby soot deposits are removed by curtailing steam generator water flow and raising fin/tube temperatures to that of the prevailing exhaust gas, is a viable alternative to standard soot-blowing practice. The results, however, also showed inconsistencies in the self-cleaning threshold temperature between the various rigs.

Phase II of this program was conducted to resolve these inconsistencies and, more specifically, to define a cleaning schedule for a LM-2500 combined cycle. The results lend further support to the self-cleaning concept and show that at full load a LM-2500 combined cycle system would be expected to clean itself within an hour after dryout.
^

1

INTRODUCTION AND PROGRAM OBJECTIVE

The combined cycle gas turbine is a means of recovering the otherwise wasted heat from the turbine exhaust gases. Rather than dumping this heat into the atmosphere, a major portion of it can now be recovered to generate steam for use in heating or process applications. A major problem, however, is the carbon or soot build-up on the heat transfer surfaces of the steam generator. This build-up reduces heat transfer, increases pressure drop, and can be a significant fire hazard.

Air or steam soot blowing devices are not always fully effective and may not be compatible with the advanced, compact matrix designs that are called for in space-limited applications such as shipboard combined cycle installations.

To eliminate the need for such mechanical soot removal devices, Solar Turbines International (STI), which is currently in the pre-production test phase of an advanced steam generator design for combined cycle applications, has made a study (Ref. 1) of the self-cleaning concept whereby soot deposits are removed by curtailing steam generator water flow and raising fin/tube temperatures to the prevailing gas turbine exhaust gas temperatures. That initial study obtained data from the following sources; (1) a gas turbine engine/boiler module, (2) a probe mounted in the exhaust duct of a LM-2500 engine and (3) a small combustor/boiler model rig. Results indicated the following:

- Demonstrated that a simple combustor rig can usefully simulate the soot fouling of a combined cycle steam generator - allows cost effective evaluation of geometry change and combustion modifications, i.e., soot emissions, fuel type, etc.
- Engine/boiler module tests have shown the relative impact of fouling throughout the steam generator and indicate the existence of an equilibrium fouling level in terms of performance deterioration.
- Further study was needed in the area of the interaction between soot deposits and the gas side corrosion products that can occur when local gas temperatures are below the sulfuric acid dewpoint temperature. It is possible that the main impact of soot fouling will not be in the area of performance degradation but in the role that soot deposits may play in catalyzing sulfuric acid condensation and magnifying corrosion effects.

This previous study, however, brought to light some inconsistencies with respect to the self-cleaning temperature. For example, furnace rig tests on

fouled, finned-tube specimens in essentially zero-velocity, hydrocarbon-free air environments showed a cleaning threshold temperature in the range 672-686°K (750-775°F). In contrast, preliminary self-cleaning tests on the combustor/steam generator model rig indicated a level of 806°K (990°F) to be required for commencement of the cleaning process.

Solar's previous experience from the Centaur engine tests of a steam generator module showed cleaning to be occurring at exhaust temperatures of 711°K (820°F) while self-cleaning of the DD-963 Conesco boiler was apparently effective down to 672°K (750°F).

The objective of this program, designated as Phase II, was to resolve these inconsistencies via an in-depth examination of the self-cleaning process with emphasis on determining the threshold temperature. More specifically cleaning schedule for a LM-2500 combined cycle system was defined. Three separate test rigs were used: (1) hot air rig, (2) furnace rig, and (3) combustor/steam generator model rig. The rationale of using three separate rigs is that the effects of the important variables such as flue gas velocity, soot loading, unburned hydrocarbons, and temperature can be more readily separated.

2

TEST EQUIPMENT AND PROCEDURES

2.1 FURNACE RIG

The furnace rig shown in Figures 1 and 2 was used to examine the basic behavior of the self-cleaning mechanism with a static gas of known composition. A soot-fouled specimen of finned tubing, mounted over a soot collection tray, is sealed inside a gas-tight container which is then placed inside a controlled temperature electric furnace shown in Figure 3. A purge gas of known composition flows at close to zero velocity through the container and exhausts outside of the electric furnace.

A typical test involved mounting the soot-fouled tube over the soot collection tray which contained thermocouples for measurement of the tube temperature and inlet and outlet purge gas temperature. This assembly was then sealed inside the cylindrical container, purged at ambient conditions so as to effect at least three volume changes. It was then placed into the electric furnace, preheated to the desired temperature, and the purge gas flow rate set as desired. The test continues for as long as required at which time the sealed container is removed from the furnace and allowed to cool prior to inspection to assess the amount of soot loss.

The air flow rate into the furnace rig also has been found to affect the degree of soot removal from the tube specimens. With very low air flows, only that portion of the tube near the air inlet sees the total affect of oxidation since as the air moves toward the outlet and more of the oxygen is reacted. Therefore, in the majority of the furnace rig tests the air flow was maintained at a sufficient rate to eliminate this variable by providing excess oxygen.

2.2 HOT AIR RIG

In terms of determining those conditions of velocity, temperature, and time, most favorable to an acceptable self-cleaning schedule, the hot air rig is a most valuable tool. It has the advantage of being simple to operate, flexible in its ability to produce a wide range of velocities and temperatures, and its physical design, i.e., tube spacing, is similar to that of a full scale unit, see Figures 4 and 5.

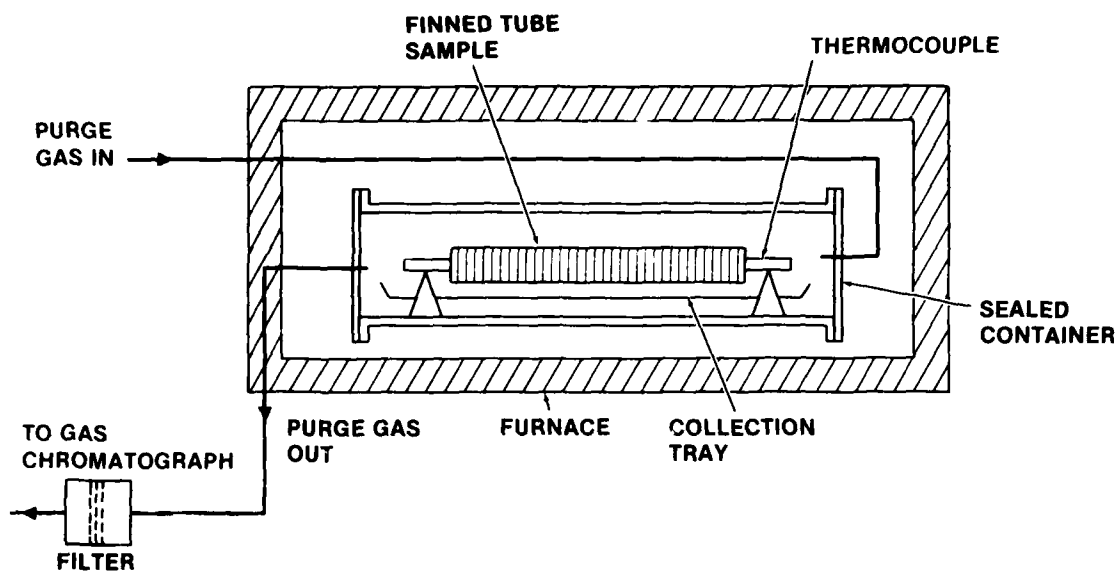


Figure 1. Furnace Rig Schematic

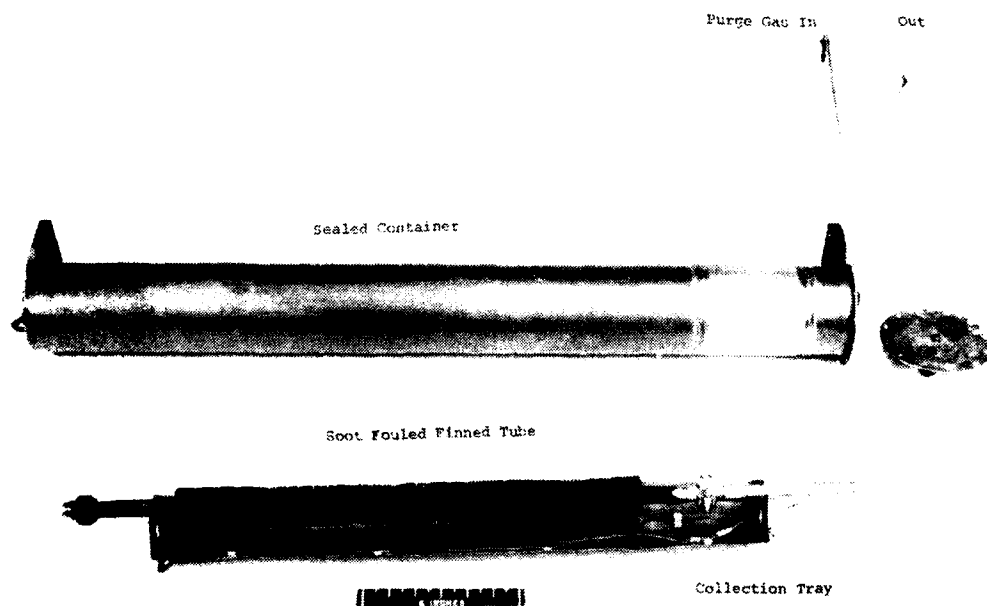


Figure 2. Furnace Rig Test Apparatus

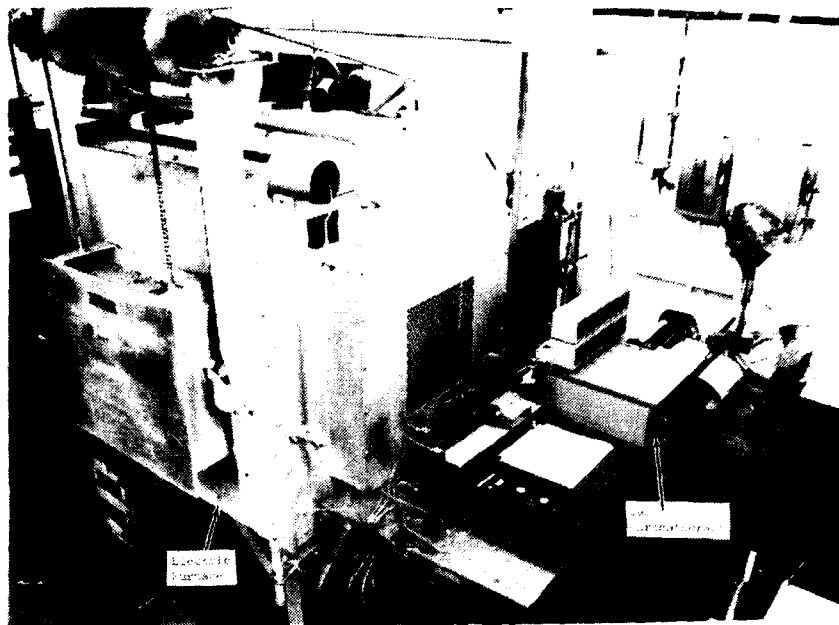


Figure 3. Furnace Rig Test Area

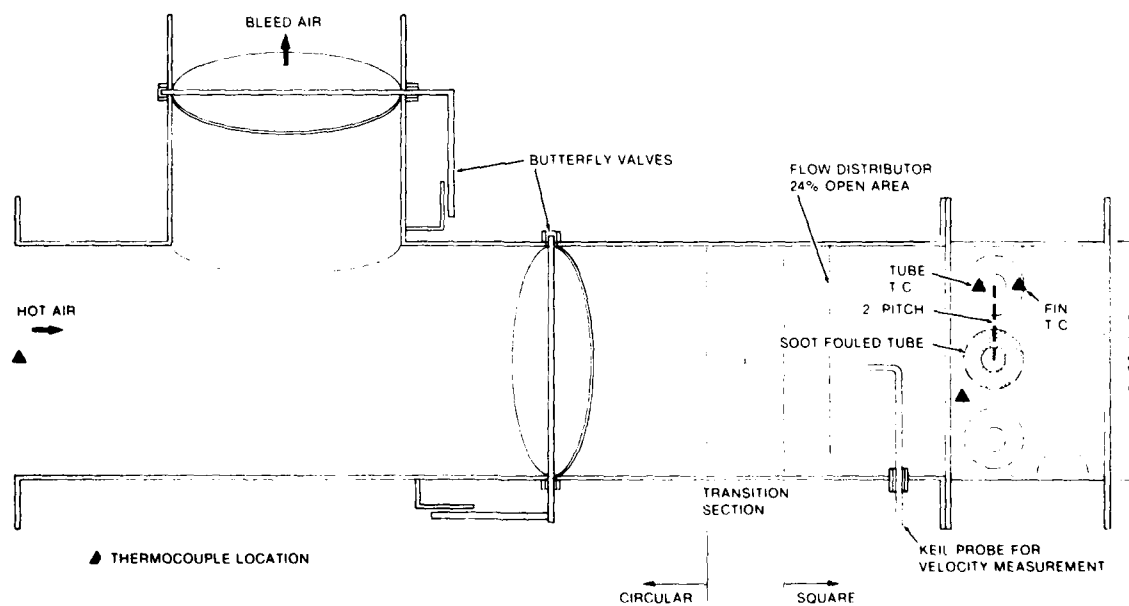


Figure 4. Hot Air Rig

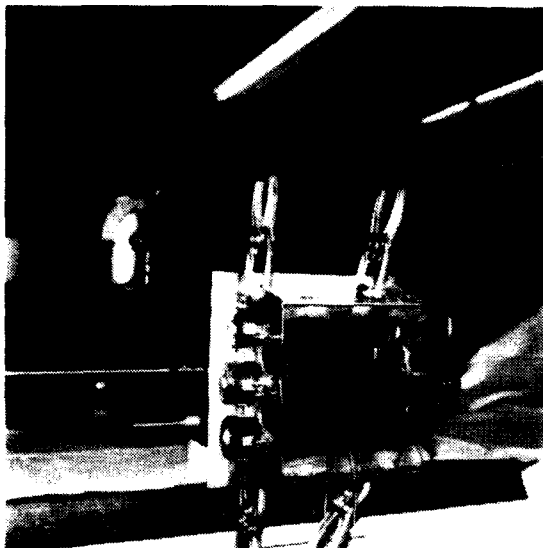


Figure 5.

Hot Air Air Rig Fouled Tube
Specimen Holder

The hot air rig consists of an air preheater, a velocity control section, and a soot-fouled tube holder clamped to the exit of the flow control section. The preheater is capable of producing heated air within the range of temperature and velocity requirements. Valving and bleed off in the velocity control section permit accurate control of these parameters. A perforated plate, 24 percent open area, assured a well distributed flow of hot air over the soot-fouled specimen. The tube holder was designed to simulate the actual air flow profile around the finned tubes. The outermost tubes were clean, finned tubes with the soot-fouled tube placed in the center position.

The finned tubing is representative of the type used in a gas turbine combined cycle steam generator designed by Solar Turbines International. The stainless steel tubes 1.59 cm (0.625 in.) diameter are finned with helically wrapped 0.71 mm (0.028 in.) carbon steel strip to produce a fin density of 2.8 fins/cm (7 fins/in). The fins are brazed to the tubing with Nicrobraz 50 which forms a continuous film over both the tubing and fin surfaces. The outside diameter of the finned tube is 3.81 cm (1.5 in).

Instrumentation consisted of a keil probe/inclined manometer for velocity measurement and thermocouples for gas, tube, and fin temperatures. It is important to note that the reported velocities for the hot air rig are those in the plane of tubes, i.e., the velocity is calculated based on the reduced cross-sectional area. This velocity is 1.67 times that in the upstream square duct. A typical temperature profile is shown in Figure 6.

A typical procedure for running a hot air rig test were as follows. The air preheater was lit off and set to bring the air up to the desired temperature. During this time the bleed air valve was wide open and the flow control valve closed. A soot-fouled tube was set into position in the tube holder,

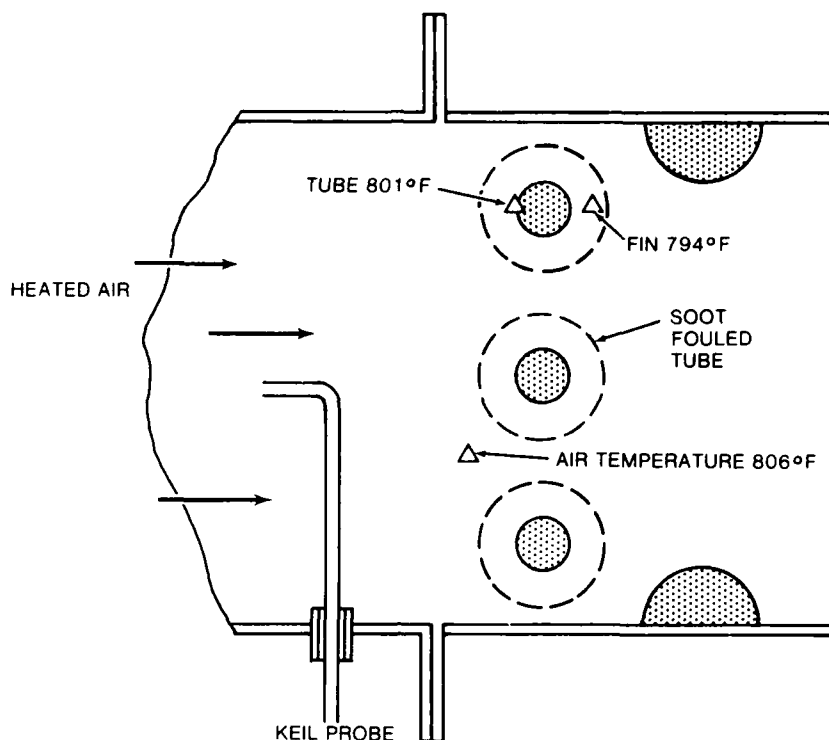


Figure 6. Hot Air Rig Temperature Profile (Typical)

then the flow control valve was opened so as to achieve the desired velocity. At the completion of the test the tube holder was removed from the hot air rig for inspection and photographs of the soot-fouled tube.

2.3 COMBUSTOR RIG

The combustor rig used in this test program is shown in Figure 7 and schematically in Figure 8, where the main features of the system can be seen. The rig consists of an atmospheric combustor stacked vertically above a steam generator model used for studying the soot fouling and cleaning phenomena.

2.3.1 Combustor

The combustor is a self-contained unit with the air supplied by a variable-speed, electric motor-driven radial fan drawing ambient air. A spinning cup fuel atomizer is mounted on the fan shaft and is used to inject a low pressure fuel into the combustor. Variable geometry is incorporated whereby an air slide controls the split of the total fan airflow to either a primary reaction air swirler or to a series of dilution ports located axially downstream of the combustor reaction zone. An alternate low pressure air supply is also available to augment the fan supplied air. Further control over the combustor exit gas temperature is afforded by a secondary dilution system

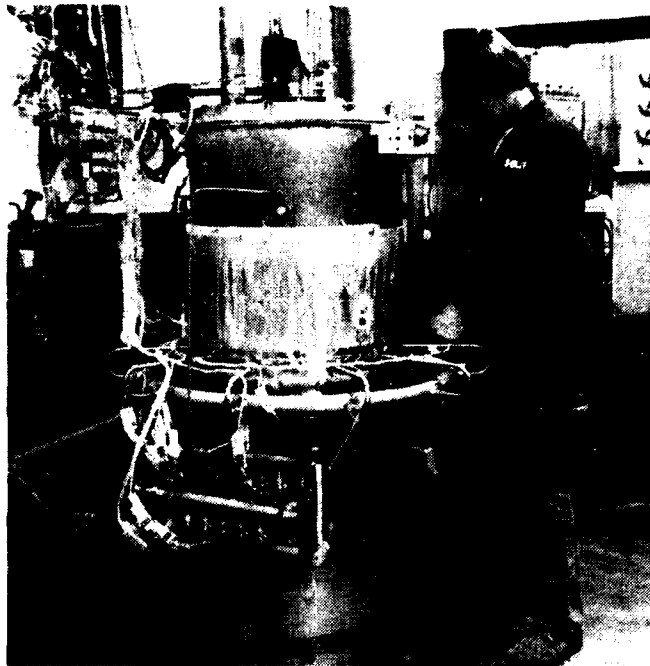


Figure 7. Combustor Rig

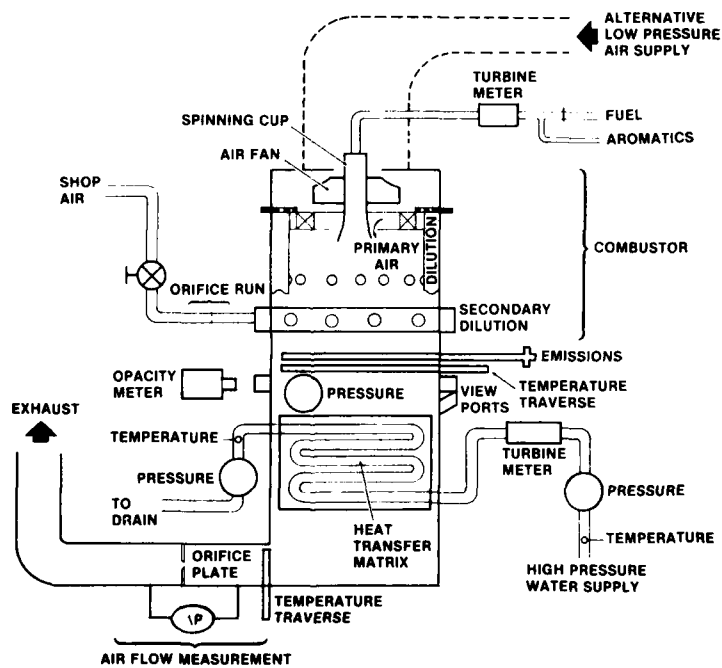


Figure 8. Combustor Rig Schematic

separately fed by a shop air supply through a ring manifold as shown in Figure 9.

The assembled combustor with the electric motor drive and air valve actuator is shown in Figure 10. A view of the belt-driven fan inlet is shown in Figure 11. A view looking into the combustor showing the spinning cup fuel atomizer is given in Figure 12.

In addition to the capability of varying airflow and fuel spray quality by modulation of the fan/cup speed, the variable geometry feature of the combustor means that the operating point, in terms of outlet temperature, velocity, and emissions can be readily controlled.

2.3.2 Steam Generator Model

The steam generator mounted below the combustor consists of a matrix of finned tubing arranged in a rectangular array four rows deep and five tubes wide. Photographs of the model arranged in alternate staggered and in-line configurations are shown in Figures 13 and 14. Figure 13 also shows the header system for supplying cooling air and/or water to the tubing.

The finned tubing is representative of the type used in a gas turbine combined cycle steam generator designed by Solar Turbines International and also used in the hot air rig. The stainless steel tubes are either 1.59 cm (0.625 in.) or 1.91 cm (0.750 in.) diameter finned with the helically wrapped 0.71 mm (0.028 in.) carbon steel strip to produce fin densities of 2.8 and 3.5 fins per cm (7 and 9 fins/inch) respectively. The fins are brazed to the tubing with Microbraz 50 which forms a continuous film over both the tubing and fin surfaces. Both water and air cooling were used during the rig testing to vary the range of metal temperatures obtainable.

The combustor rig served two purposes, (1) it was run under sooting conditions to generate a supply of soot-fouled tubes for use in the hot air rig, and (2), it was used in an attempt to determine the threshold temperature for self-cleaning under actual flue gas conditions, i.e., a Diesel #2 flue gas rather than just heated air.



Figure 9.

Secondary Dilution Air Manifold

Figure 10.

Combustor Assembly

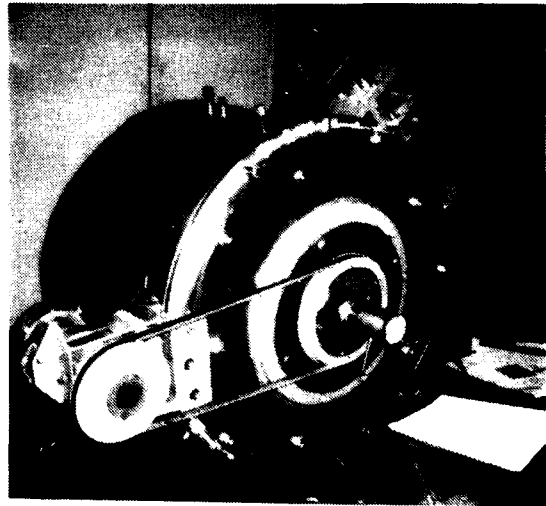


Figure 11.

Air Supply Fan Inlet



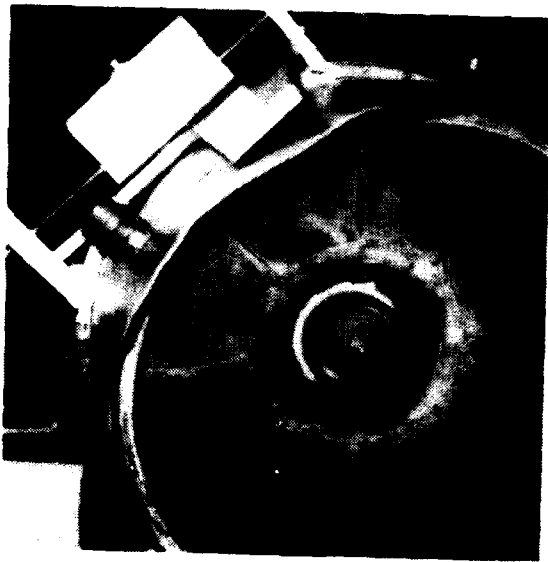


Figure 12.
Rotating Cup Fuel Injector

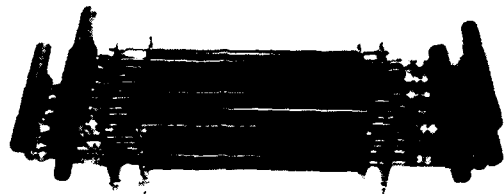


Figure 13.
Steam Generator Test Model Staggered
Tubing Configuration

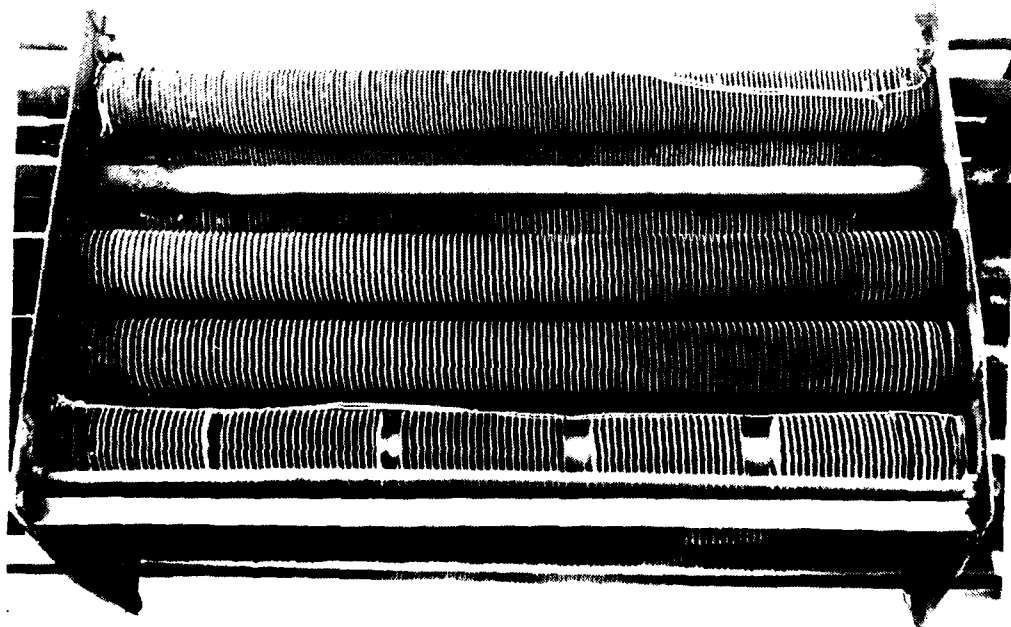


Figure 14. Combustor Rig In-Line Tubing Configuration

3

RESULTS AND DISCUSSION

3.1 SOOT LOSS AND SOOT-FOULED TUBES

In the discussions to follow repeated reference will be made to "XX% of soot removed". These assessments of the amount of soot removed are based on visual observation and are related to the surface area of the finned tube which has been completely cleaned of soot. This method is applicable since the mechanism of soot removal seems to be a flaking off of the total thickness of the soot deposit rather than a gradual reduction in thickness.

All of the soot-fouled tubes used in this program were generated using the combustor rig/boiler model. The fouled tubes in use to 10/17/79 were generated in 1/79 via combustion of Diesel No. 2 fuel under sooting conditions. On 10/17/79 and 11/21/70 "fresh" sets of soot-fouled tubes was generated via combustion of Diesel No. 2 fuel.

3.2 FURNACE RIG TESTS

3.2.1 Air Atmosphere

The majority of the furnace rig tests were run using a hydrocarbon free (<0.1 ppm) air atmosphere with temperatures in the 533-783°K (500-950°F) range. A summary of the furnace rig tests in the form of a "cleaning schedule" is presented in Figure 15. The data used to compile this "cleaning schedule" was obtained, for the most part, using "aged" soot fouled tubes, i.e, the tubes had been exposed to ambient conditions for six to nine months. As will be seen these "aged" tubes are more amenable to cleaning than "fresh" soot fouled tubes.

These tests indicate a threshold temperature of about 756°K (900°F), above which a significant increase in the soot removal rate is seen to occur. At temperatures much below 756°K (900°F) some cleaning does occur but much longer times are required.

The mechanism for soot removal in these furnace rig tests seems to be two-fold; (1) oxidation of the soot and (2) breaking of the soot-metal bond followed by flaking off of the soot. Oxidation is evidenced by the fact that some of the soot simply "disappears" and only oxidation to CO and/or CO₂ would account for this. (Previous analysis of the soot in Phase I has

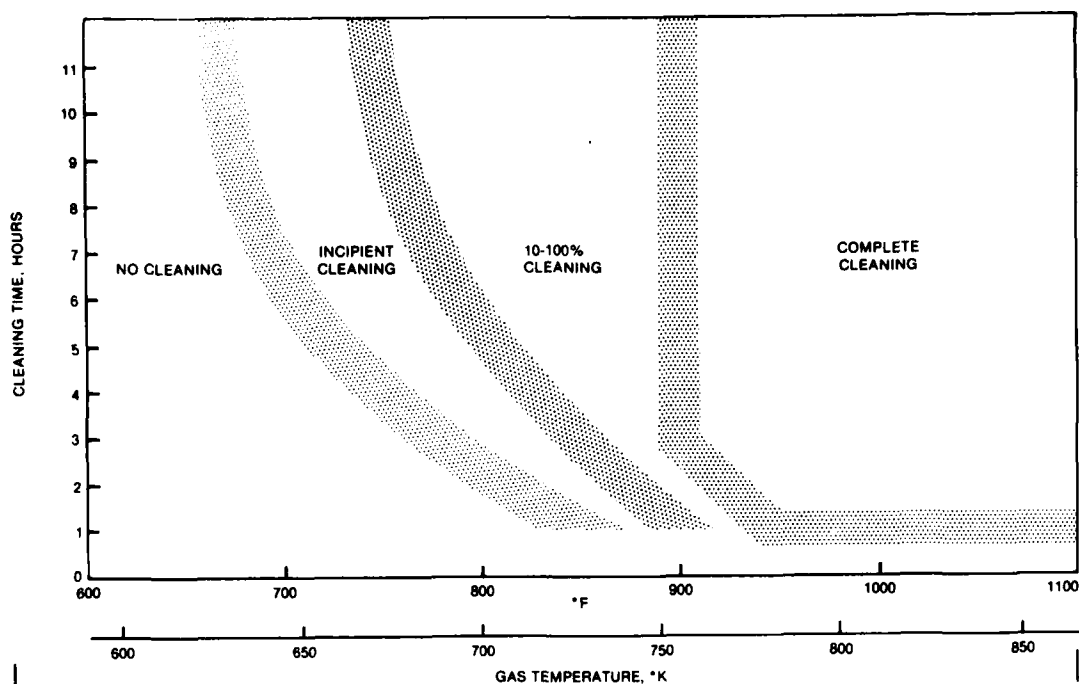


Figure 15. Cleaning Schedule Furnace Rig Tests

shown it to be approximately 75 percent carbon.) The second "mechanism" may also be a result of oxidation of the soot at the soot-metal interface.

3.2.2 Inert Gas Atmosphere

A number of furnace rig tests were run using an inert gas atmosphere of either argon/helium or pure helium during which soot fouled tubes were subjected to temperatures ranging from 589-867°K (600-1100°F) for periods of up to twenty-two (22) hours. No soot loss or change in its physical appearance was noted in any of these tests. These results lend additional support to oxidation as the basic mechanism in soot removal. If the mechanism of soot adhesion is due to the "glueing" together of the soot particles by condensed hydrocarbons, some changes could have been expected in heating to high temperature for long periods. No such changes were noted.

3.2.3 Fuel Vapors and Hydrocarbon Gases

Since methane was always found as a constituent of the off-gas when heating soot and, it might be expected that under certain conditions, such as start-up, that unburned fuel vapors would be present in the exchange gas, testing was conducted to determine the effect of this on soot removal. First, tests were run with 186 ppm methane, balance helium, at 644°K (700°F) and 700°K (800°F) for 1.5 and 2.0 hour periods, respectively. Results indicated no effect. This, however, would be expected as no oxidizer was present.

The second set of tests in this series sought to determine the effect of 1750 ppm methane in air on soot removal at a temperature of 756°K (900°F). Results indicated that although there was some soot removal, comparison with hydrocarbon-free air tests indicate a slight tendency for the methane to inhibit soot removal.

To determine the effects of unburned fuel vapors on soot loss a test was conducted whereby air was bubbled through Diesel No. 2 fuel and used as the purge gas for a furnace rig test. At ambient temperature the expected vapor pressure of Diesel No. 2 fuel in air is in the order of 300-500 ppm. A one hour test at 783°K (950°F) indicated no effect of the fuel vapor on soot removal.

3.3 HOT AIR RIG TESTS

The majority of the testing was done using the hot air rig because of its ability to simulate the actual operating environment of a soot-fouled tube. Although only heated air was used, in contrast to a gas turbine exhaust gas, the previous tests indicated that hydrocarbon and/or fuel vapors had little effect on soot removal.

It should be pointed out that the following results were obtained from soot derived from Diesel No. 2 combustion and in most cases the soot had been in contact with ambient air for at least six months. As will be discussed in the following sections this "ageing" of soot tends to affect how easily it is removed and, in addition, it is probable that soot derived from different fuels will behave differently. These following results, therefore, must be analyzed with these points in mind.

3.3.1 Effect of Time, Temperature and Velocity

Figure 16 summarizes in graphical form the results of the hot air rig tests aimed at determining a threshold temperature for self-cleaning. The majority of these tests were run at conditions expected for a full size LM-2500 combined cycle system, i.e., temperatures to 783°K (950°F) and velocities in the 15.2-27.4 m/s (50-90 ft/sec) range. This threshold temperature is defined as the lowest temperature which, in an hour's time, will result in approximately 95 percent soot removal given a gas velocity in the 15.2-27.4 m/s (50-90 ft/sec) range.

From Figure 16 it is apparent that the threshold temperature is 756°K (900°F); this compares favorably to that of the furnace rig tests. At lower temperatures some cleaning can be accomplished, but with increased treatment time. At very high velocities, greater than 30.5 m/sec (100 ft/sec), temperature becomes less important as the airblast effects predominates.

Figures 17 through 20 are photographs of soot-fouled tubes before and after various time, temperature, velocity treatments in the hot air rig. The photos show a progression of increased self-cleaning.

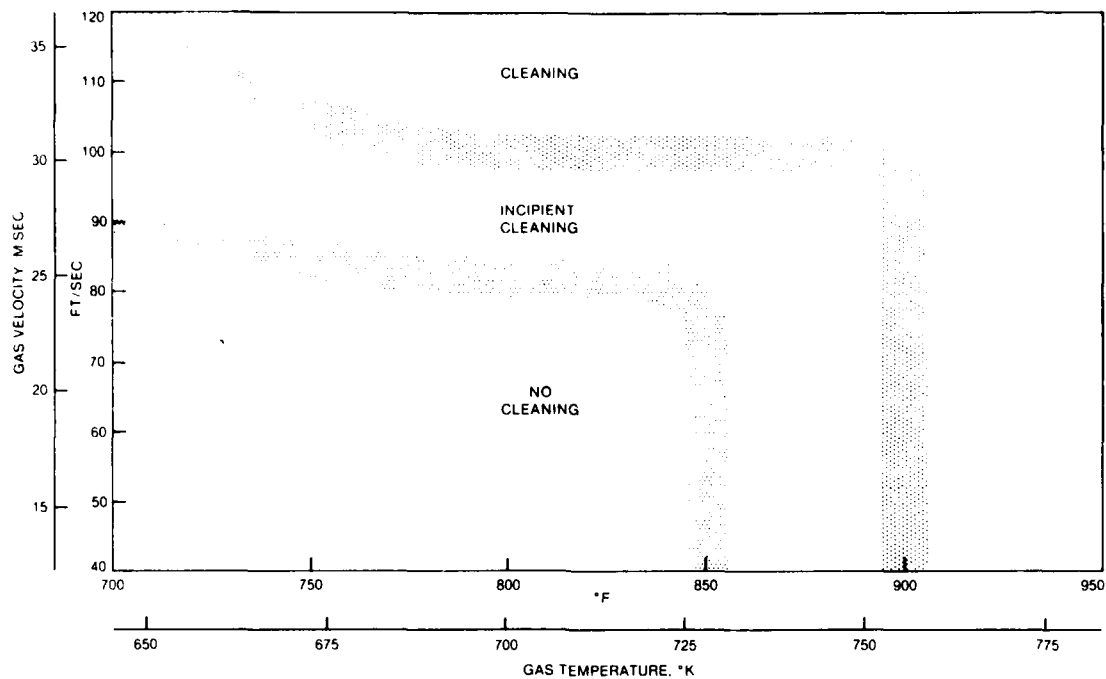


Figure 16. Cleaning Schedule Hot Air Rig Tests



Figure 17.
Soot-Fouled Tube Prior to
Treatment - Hot Air Rig

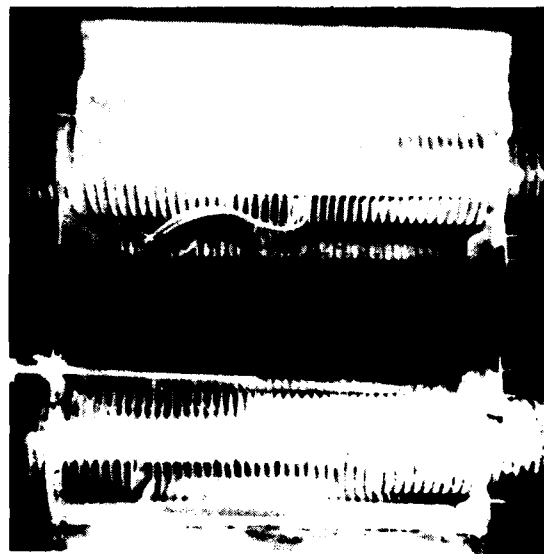


Figure 18.
Soot-Fouled Tube After One Hour at
728°K (850°F) and 12.2 m/s (40 ft/sec)
- Hot Air Rig

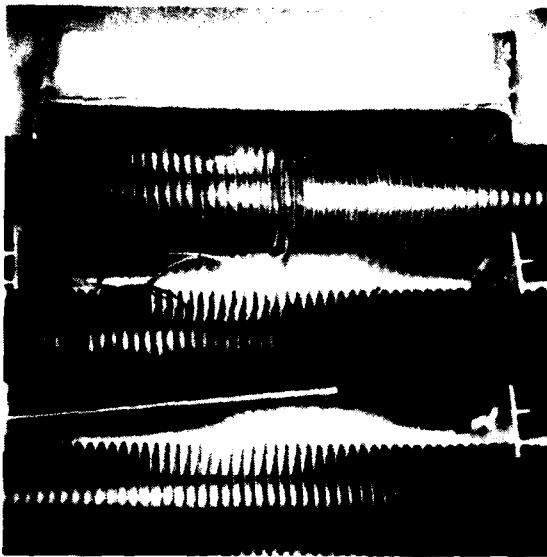


Figure 19.

Soot-Fouled Tube After One-Half Hour at 756°K (900°F) and 18.3 m/s (60 ft/sec) - Hot Air Rig

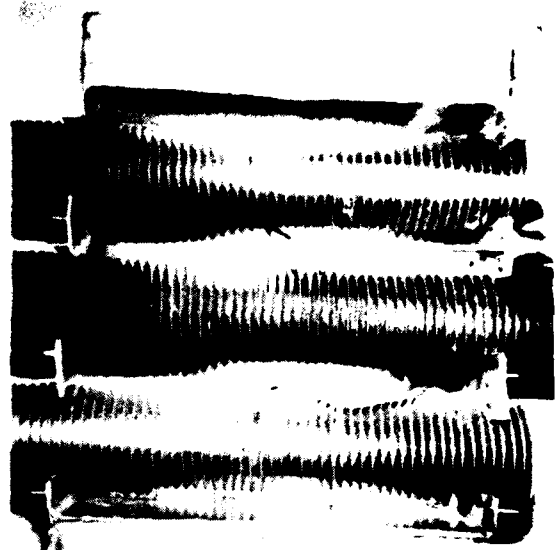


Figure 20.

Soot-Fouled Tube After One-Half Hour at 783°K (950°F) and 18.3 m/s (60 ft/sec) Hot Air Rig

During the majority of the hot air rig tests run with air temperatures of 756°K+ (900°F+) the soot would suddenly and sporadically begin to oxidize as evidenced by the glowing embers and sparklers exiting the rig. When this action did occur it was always within the first minute or so of the test. Those areas which had oxidized, and had not flaked off, were easily identified due to the off-white color of the remaining ash.

3.3.2 Fuel Vapors and Hydrocarbon Gases

As in the previously described furnace rig tests, the effect of fuel vapors and hydrocarbon gases on self-cleaning were evaluated. The first test used injection of Diesel No. 2 fuel into the hot air stream to give a vapor concentration in the 200-700 ppm range. Test conditions were 783°K (950°F) at 10.7 m/s (35 ft/sec) for 30 minutes. As was the case in the furnace rig test no effect of the fuel vapor on soot loss was observed.

For the second test methane was injected into the heated air stream to give a concentration of 1000 ppm; rig conditions were 728°K (850°F) at 10.7 m/s (35 ft/sec) for one hour. Comparison to other tests without methane injection indicate that this hydrocarbon may have exhibited a slight tendency to inhibit the soot loss.

3.3.3 Surface Coatings and Finishes

Also investigated was the effect of surface coatings on both soot retention and removal. Four coatings were evaluated, they were:

- | | |
|-----------------------------|---|
| 1. Nickel-chromium-aluminum | } Plasma sprayed
characterized by rough surface
~200 microinches r.m.s. |
| 2. Cobalt-chromium-aluminum | |
| 3. Aluminum | |
| 4. Solaramic® S-20-1 | Vitreous coating
Glass-like finish |

Each of the coatings was applied over one-half the length of a finned tube. These tubes were then assembled into the boiler model. The combustor rig was operated at soot producing conditions to obtain a soot build-up on the tubes. During the sooting up process none of the coatings showed any tendency to shed or inhibit soot fouling when compared to an uncoated surface.

After the tubes had acquired a soot build-up the coated sections were individually evaluated on the hot air rig to determine any increased tendency toward soot shedding during a simulated "self cleaning". Figure 21 shows a soot-fouled coated tube prior to a hot air rig test. Each of the coated sections and a control uncoated surface were run at 728°K (850°F) at 10.7 m/s (35 ft/sec) for one-half hour. The rough surfaced metal coatings did not prove to be any better than an uncoated surface in shedding of soot. The very smooth Solaramic® S-20-1 coating displayed a significant increase in soot shedding ability. Whereas the control and metal coated specimens lost no soot, the Solaramic® S-20-1 coated section affected a 60 percent and 20 percent cleaning from the front and back portions of the tube respectively shown in Figure 22. The soot remaining on the Solaramic® coated section was very loosely held in place due to the closeness of the fin spacing. For these tests the surface finish, rather than the chemistry of the coating, seemed to be the controlling factor.

3.3.4 Commercial Slag/Soot Removal - Gamlenite 13C®

Gamlenite 13C® (Gamlen Chemical Company) is used in industry as a chemical method of eliminating combustion deposits and slag from boiler tube surfaces and refractories. Its normal use is with coal fired equipment but it has other applications in units burning oil, waste gas or organic matter. The manufacturer claims that when Gamlenite is injected in the furnace, it forms a dense reactive vapor which reacts with the combustion deposits to:

- raise their fusion temperature
- weaken the bonding of the deposits

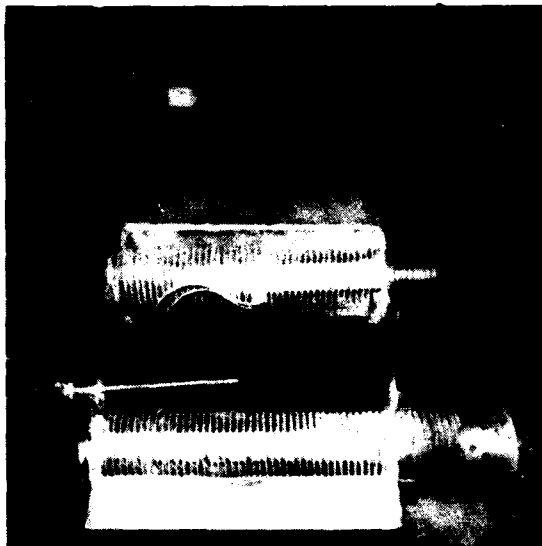


Figure 21.

Soot-Fouled Solaramic® Coated
Tube - Hot Air Rig

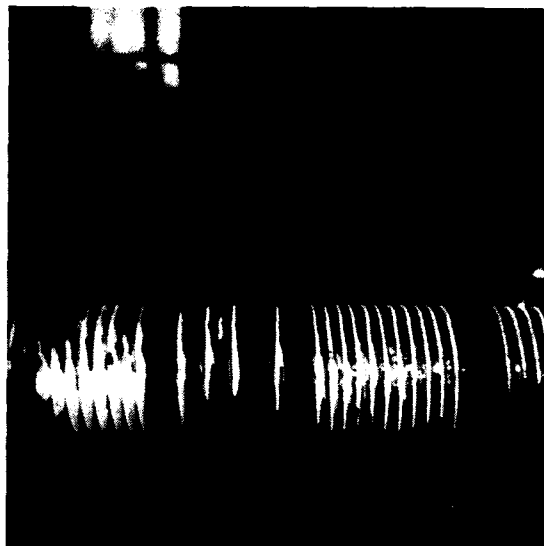


Figure 22.

Soot-Fouled Solaramic® Coated Tube
After One-Half Hour at 728°K (850°F)
and 10.7 m/s (35 ft/sec)

An important point is that Gamlenite® is intended to be injected into the furnace whereupon it forms a vapor at the high temperatures involved, 1367°K (2000°F+). In the hot air tests, however, the Gamlenite® was injected in a 756°K (900°F) hot air stream with very little, if any, vaporization taking place. Even so, it was very effective in removing the soot but this was due to the scouring action of the Gamlenite® particles rather than any chemical reaction.

3.3.5 Fuel Soaked Soot

Considering that a gas turbine may experience aborted starts, which can result in previously deposited soot being soaked with raw fuel, tests were conducted to determine the ignition characteristics of such soot. A number of tests were run using Diesel No. 2 to saturate the soot. Table 1 summarizes the results.

The procedure for these tests involved soaking a soot-fouled tube with fuel from a spray bottle. The tube was then placed in the tube holder and clamped on the back of the hot air rig during which time the hot air was by-passed through the bleed. The valves were then adjusted so as to bring the hot air over the tube. If a tube autoignited it would do so within 15 seconds otherwise the fuel would merely vaporize to a cloud of white vapor. Of the tubes that did autoignite the amount of soot removal or cleaning experienced varied from 50 percent to 100 percent. However, considering the dangers involved this is not a recommended cleaning procedure.

Table 1

Fuel Soaked Soot
Hot Air Rig Test Results
(9.14-15.2 m/s [30-50 ft/sec] air velocity)

Hot Air Temperature (°F)		
756°K (900+°F)	Soot autoignition	2 out of 2 attempts
700°K (800°F)	Soot autoignition	0 out of 3 attempts
644°K (700°F)	Soot autoignition	1 out of 4 attempts

The data confirm the fact that there is a danger of fire in a steam generator containing soot fouled tubes saturated with raw fuel although the potential damage would be strongly dependent upon whether the unit was operating "dry".

3.3.6 "Fresh" Versus "Aged" Soot

The majority of the tests, both hot air and furnace rig, were conducted using soot-fouled tubes generated in 1/79. These "aged" tubes, stored at ambient conditions, were used until 10/17/79 at which time "fresh" soot-fouled tubes were produced. In addition two "artificially aged" tubes were produced from the "fresh" tubes by placing them in a 367°K (200°F) oven for eight (8) hours.

The trend of the results indicate that at temperatures in the range 800-850°F and at 10.7 m/s (35 ft/sec) there does not seem to be any difference in soot removal between the "fresh" and "aged" soot fouled tubes. Tests run at 783°K (950°F) and 10.7 m/s (35 ft/sec), however, tend to indicate a significant increase in soot removal when going from a "fresh" to an "aged" tube. Both the "aged" and "artificially aged" [heated for 8 hours in oven at 367°K (200°F)] soot fouled tubes showed about the same cleaning characteristics.

Another important observation is that hot air rig testing with one week old "fresh" tubes exhibited very little soot loss compared with two and three week old "fresh" tubes run under similar conditions which showed about 50 percent and 20 percent soot loss from the front and back portions of the tubes, respectively. The implication is that some change is taking place in the soot which seems to be completed after about one week's exposure to ambient conditions.

3.3.7 Thermal Cycling

It had been observed in previous hot air rig tests that when a tube was subjected to two one-half hour treatment periods, with an instrumentation inspection at ambient conditions that all or the majority of the soot loss occurred during the second period. It therefore appears that allowing the tube to cool followed by replacement in the hot air stream shocks the soot in a manner which aids its removal. To test this concept two tests were run, one for one-half hour and the other for one hour at 728°K (850°F) and 12.2 m/s (40 ft/sec). In both tests no soot removal was observed. This is in contrast to a previous "one hour" test at similar conditions which was split by an inspection at the half hour point. The first half hour showed no soot loss but the second half hour resulted in 40-50 percent soot loss from the front portion of the tube. These results tend to indicate that thermal cycling of a soot fouled tube may aid soot removal. These results are summarized in Table 2.

3.4 COMBUSTOR RIG TESTS

A single combustor rig test was conducted in the self-cleaning mode, i.e., water cooling to the steam generator module was shut off to bring the finned tubes up to prevailing gas temperature. The boiler module contained two Solaramic® S-20-1 coated finned tubes which had, along with the other tubes, previously been soot fouled.

During this test there were only a few instances of rapid oxidation of the soot as characterized by glowing embers. This was confined to two small areas. Due to the transient nature of the test, i.e., the fin temperature being continually increased, there was no clearly defined self-cleaning threshold temperature observed.

3.5 RESULTANT CLEANING SCHEDULE

An objective of the test program was to determine the cleaning schedule for a LM-2500 combined cycle system. Figure 23 depicts such a cleaning schedule based on the data obtained in this test program combined with known LM-2500 operating conditions. No attempt has been made to account for various fin spacings, different types of soot, soot thickness, etc.

The "cleaning time" is based on the time required to effect a 95%+ removal of soot, down to bare metal, from soot-fouled tubes on a fin/tube surface area basis. This does not imply, however, that a 95 percent soot removal will result in recovery of 95 percent of the net loss in heat transfer efficiency. No attempt was made in this test program to estimate the loss of heat transfer efficiency due to soot build-up.

Table 2

Hot Air Rig Results
Thermal Cycling

12.2 m/s (40 ft/sec) - 728°K (850°F) - 1 Hour	No soot loss
12.2 m/s (40 ft/sec) - 728°K (850°F) - 1/2 Hour	No soot loss
12.2 m/s (40 ft/sec) - 728°K (850°F) - 1/2 + 1/2 hour	40-50% Loss (Front)

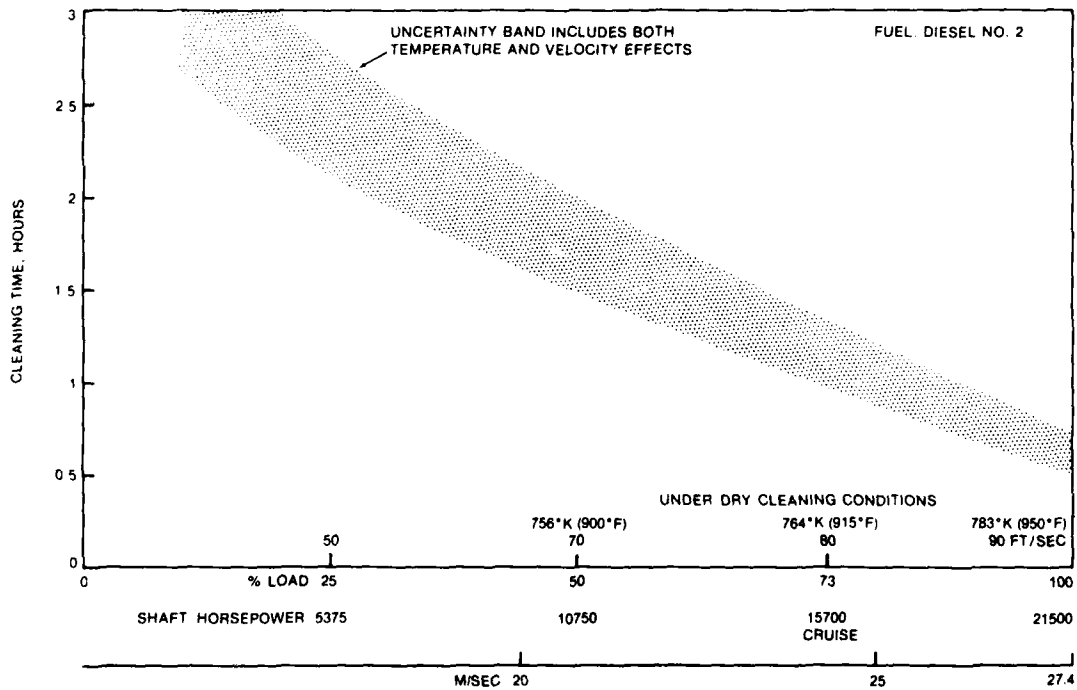


Figure 23. LM-2500 Cleaning Schedule

The data does indicate that at full load [21,500 shp, 783°K (950°F), 27.4 m/s (90 ft/sec)] it would be expected that a soot fouled heat exchanger would be restored to an "as built" condition in about half an hour.

4

CONCLUSIONS AND RECOMENDATIONS

- . Added information was generated to support the self-cleaning concept as a viable alternative to conventional soot blowing practices. Sufficient data were obtained in the test program to permit the development of a "cleaning schedule" as a function of the General Electric LM-2500 gas turbine operating condition.
- . The major parameters controlling the fouling and cleaning processes are time, temperature and velocity. Testing also showed that surface finish, soot aging, trace hydrocarbons, and thermal cycling have various effects on the soot removal mechanism.
- . Further study is needed in the area of the interaction between soot deposits and the gas side corrosion products than can occur when local gas temperatures are below the sulfuric acid dewpoint temperature. It is possible that the main impact of soot fouling will not be in the area of performance degradation but in the role that soot deposits may play in catalyzing sulfuric acid condensation and magnifying corrosion effects.

5

OVERALL PROGRAM ACHIEVEMENTS

- . Demonstrated that a simple combustor rig can usefully simulate the soot fouling of a combined cycle steam generator - allows cost effective evaluation of geometry changes and combustion modifications (soot emissions, fuel type).
- . Engine/boiler module tests have shown the relative impact of fouling throughout the steam generator and indicate the existence of an equilibrium fouling level in terms of performance deterioration.
- . Defined the major parameters controlling the fouling and cleaning processes.
- . Demonstrated that self-cleaning is a viable alternative to conventional soot blowing techniques - can result in essentially 'as clean' performance.
- . Generated a suggested 'self-cleaning time required' schedule as a function of LM-2500 operating condition.

6

SUMMARY

Liquid-fueled gas turbines can produce serious steam generator fouling in combined cycle applications and other waste heat recovery systems. Compact matrix designs, compatible with gas turbine packaging, may not be compatible with standard "soot blowing" practices. Therefore, Phase I of this test program was conducted to investigate the effects on gas side soot fouling rates of various operational parameters such as soot loading, metal temperatures, and velocity. Particular attention was given to the effectiveness of the self-cleaning concept where elevated steam generator metal temperatures obtained by dry running are utilized to remove soot deposits.

It became apparent that the results from the various Phase I rig tests were inconsistent with respect to the self-cleaning threshold temperature. Furnace rig tests on fouled, finned-tube specimens in essentially zero-velocity, hydrocarbon-free air environments showed a cleaning threshold temperature in the range 672-686°K (750-775°F). In contrast, preliminary self-cleaning tests on the combustor/steam generator model rig indicated a level of 806°K (990°F) to be required for commencement of the cleaning process.

Solar's previous experience from the Centaur engine tests of a steam generator module showed cleaning to be occurring at exhaust temperatures of 820°F while self-cleaning of the DD-963 Consec boiler was apparently effective down to 672°K (750°F).

In order to resolve these inconsistencies, the contract was extended (Phase II) to allow time for an in-depth study of the self-cleaning concept with emphasis on determining the threshold temperature. More specifically we sought to define a cleaning schedule for a LM-2500 combined cycle system.

During this extension, designated as Phase II, three separate test rigs were used: (1) hot air rig, (2) furnace rig, and (3) combustor/steam generator model rig. The rationale of using three separate rigs is that the effects of the important variables such as flue gas velocity, soot loading, unburned hydrocarbons, and temperature could be more readily separated.

The controlling variables were found to be temperature, time, and velocity with temperature being the most dominant. The threshold temperature for self-cleaning was found to be at about 756°K (900°F). That is, at this gas temperature with velocities in the 15.2-27.4 m/s (50-90 ft/sec) range, about 95 percent of the fin/tube surface area will be cleaned within an hour's time. At temperatures greater than 756°K (900°F) soot removal is significantly accelerated.

Two mechanisms appear to be involved in the self-cleaning concept; (1) oxidation and (2) physical removal. The furnace rig tests, run at zero velocity, indicate that oxidation of the soot alone can effect a significant degree of soot removal. The furnace rig tests also point out that oxidation is the key element in the loosening of the soot-metal bonds which then makes possible the physical removal of the soot via the impact forces of the flowing gas. The importance of oxidation is also borne out by the fact that furnace rig tests run with inert atmospheres showed no effect whatsoever on the soot. Hydrocarbon gases and raw fuel vapors were found to have a very slight retarding effect on soot loss.

A very smooth, glass-like finish on the surfaces was found to appreciably aid in soot removal. However, these same smooth surfaces exhibited no tendency to inhibit the initial soot build-up.

Hot air rig tests showed that fuel soaked soot could spontaneously autoignite. Such testing was conducted with gas temperatures in the 644-756°K (700-900°F) range. Repeatability of ignition was poor with only three of nine attempts resulting in ignition. No was damage observed.

The "age" of the soot, or the time that it has been exposed to an oxidizing atmosphere, was seen to have an effect on the ease of soot removal. "Aged" soot was more easily removed in contrast to a "fresh" soot, i.e., less than a week or two old.

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